

RIDGE WAVEGUIDE SEMICONDUCTOR LASER DIODE

RELATED APPLICATIONS

[0001] This application is a continuation-in-part of U.S. patent application serial number 09/872,334, filed June 1, 2001, which is a continuation-in-part of U.S. patent application serial number 09/201,245, filed November 30, 1998, the entire contents of the above-identified applications being incorporated herein by reference.

FIELD OF THE INVENTION

[0002] The present invention relates to a ridge waveguide semiconductor laser diode, and more particularly, to a ridge waveguide semiconductor laser diode having a high output power and an excellent laser characteristic and capable of operating at a higher output power with excellent stability.

BACKGROUND OF THE INVENTION

[0003] GaAs-based quantum-well laser diodes each having an InGaAs strained quantum-well active layer or layers, especially ridge waveguide semiconductor laser diodes, have been intensively researched and developed as feasible higher-output power semiconductor laser diodes or light sources in optical devices for use in wavelength division multiplexing (WDM) systems. With the development of WDM systems, it is desired to further increase the optical output power of the ridge waveguide semiconductor laser diode.

[0004] In addition, the GaAs based ridge waveguide semiconductor laser diode attracts attention as a light source for use in an erbium-doped fiber amplifier (EDFA).

[0005] Referring to FIG. 1, a typical GaAs-based quantum-well laser diode will be described as an example. A layer structure 10 of a conventional ridge waveguide GaAs laser diode includes, for instance, a buffer layer 14 having GaAs or AlGaAs based compound semiconductor layer, a lower cladding layer 16, a first optical confinement layer 18, a second optical confinement layer 20, a first strained quantum-well layer 22, a barrier layer 24, a second strained quantum-well layer 26, a third optical confinement

layer 28, a fourth optical confinement layer 30, a first upper cladding layer 32, an etch stop layer 34, a second upper cladding layer 36, and a cap layer 38 consecutively formed on a n-GaAs substrate 12. The second upper cladding layer 36 and the cap layer 38 overlying the etch stop layer 34 have a mesa structure. The quantum-well layers 22,26, the barrier layer 24, and optical confinement layers 18,20,28,30 are oftentimes referred to as the active layers.

[0006] The chief factor for restricting the increase of the optical output power from the GaAs based ridge waveguide quantum-well laser diode (hereinafter referred to as simply GaAs quantum-well laser diode) is catastrophic optical damage (COD) which signifies that the optical facet of the laser diode is damaged instantaneously. When the optical output power increases to reach a specific value, the COD which is inherent in the GaAs based laser diode is generated to stop the function of the laser diode at that instant.

[0007] For preventing the generation of COD failure, for instance, a conventional wide mesa structure of about $4\ \mu\text{m}$ is adopted to decrease the optical density in the active layers; however, in case of the wide mesa structure, a so-called spatial-hole-burning phenomenon occurs wherein the optical gain of the laser diode is uneven in the direction parallel to the axis of the active layers arises to thereby tend to generate a beam steering phenomenon.

[0008] The beam steering phenomenon is known in the art and it means that the light beam moves in the direction parallel to the active layers (as viewed from the front facet of the laser), which causes the characteristic of the optical output with respect to injected current in the semiconductor laser diode to be non-linear by having one or more kinks in the characteristic, thereby deteriorating the laser characteristic significantly.

The non-linearity means that the external differential quantum efficiency " η " ($\eta = dL_{\text{OUT}}/d(I - I_{\text{TH}})$) does not remain as a constant, wherein " L_{OUT} " represents the optical output, " I " represents the injected current at the optical output of " L_{OUT} ", and " I_{TH} " represents a threshold current. In a more extreme case, " η " sometimes becomes almost 0. Accordingly, signal conversion cannot be effected from the injected current due to the deteriorated laser characteristic. This is particularly critical when the laser diode is

coupled to an optical fiber.

[0009] For preventing the generation of the problem beam steering phenomenon in a high output power range, it is necessary to consider complicated and various effects, such as the waveguide mode control of the active layers, and thus the problem is not solved in the conventional GaAs quantum-well laser diode.

[0010] In addition, it is important to obtain an operational stability in the laser diode's output at higher output power levels, especially in the stability of the transverse and longitudinal modes of the diode when one uses a GaAs-based quantum-well laser diode as a light source for a WDM system.

[0011] As another application, a new optical module wherein a GaAs-based quantum-well laser diode and a fiber Bragg grating (FBG) for controlling the lasing wavelength and gain of the diode are integrated together is now being put to practical use as the pumping light source for erbium-doped fiber amplifiers (EDFAs). However, if a GaAs-based quantum-well laser diode having a lasing wavelength of 980 nm is used as a light source for an EDFA, the longitudinal mode operation is unstable when light returns from the FBG, whereby the optical output power fluctuates to cause another problem.

[0012] In the above description for the problems in the ridge waveguide semiconductor laser diodes, a GaAs-based quantum-well laser diode is exemplified. However, these problems are not peculiar to the GaAs-based quantum-well laser diode, but are common to general ridge waveguide semiconductor laser diodes.

SUMMARY OF THE INVENTION

[0013] It is therefore an object of the present invention to provide a ridge waveguide semiconductor laser diode having a linear characteristic between the optical output power and the injected current in a higher optical output range.

[0014] It is another object of the present invention to provide a ridge waveguide semiconductor laser diode which is capable of operating with excellent stability in both of its transverse and longitudinal modes.

[0015] It is still another object of the present invention to provide a ridge waveguide semiconductor laser diode which is capable of operating with a FBG in a stable manner

to provide a stable light source for the EDFA.

[0016] The present invention provides a ridge waveguide semiconductor laser diode including a semiconductor substrate, at least one active layer overlying the semiconductor substrate, and at least one cladding layer overlaying the at least one active layer. The at least one cladding layer includes a ridge structure part having a length L along the direction of light propagation, a width S which is perpendicular to the length L and parallel to the surface of the at least one active layer, and a thickness T which is perpendicular to the width and the length. The at least one cladding layer further includes a remaining part which is a sub-layer disposed between the ridge structure part and the at least one active layer. The remaining part overlies at least the portions of the active layer(s) which are within a relatively short distance of either side of the ridge structure part. This relatively short distance is typically around a value of $2 \cdot W_H$, where " W_H " is the horizontal width of the laser spot emanating from the laser diode's front facet, as measured at the front facet and as measured in the direction which is parallel with the plane of the active layers (as viewed from the front facet). However, in some preferred embodiments of the present invention, the remaining part of the cladding layer(s) overlies substantially the entire surface of the active layer(s).

[0017] For applications where the laser diode is not used with an FBG, or other type of wavelength selector, positioned in front of diode's emitting facet, the remaining part has a thickness "D" in the range of:

$$D \geq \frac{1}{2}W,$$

wherein "W" is the width of the laser spot emanating from the laser diode's front facet, as measured at the front facet and as measured in the direction which is perpendicular to the plane of the active layers (as viewed from the front facet). The width is measured at the points of the spot where the light power level has a value which is $1/e^2$ of the maximum power level at the center of the spot, with "e" being the base of the natural logarithm ($e=2.71828...$). In practice, and as described below in greater detail, the width of the spot can be readily measured from the vertical divergence angle in the laser's far field pattern (the latter of which is a projection of the laser spot onto a planar surface spaced at a distance from the laser diode's front facet, and parallel thereto).

[0018] For applications where the laser diode is used with an FBG, or other type of wavelength selector, positioned in front of diode's emitting facet, the remaining part has a thickness "D" within the range of:

$$1.10 \times W > D \geq \frac{1}{2}W,$$

5 and more preferably within the range of:

$$1.05 \times W > D \geq \frac{1}{2}W,$$

and most preferably within the range of:

$$W > D \geq \frac{1}{2}W.$$

[0019] In accordance with the semiconductor laser diode of the present invention, due to the value for "D", the kink phenomenon in the characteristic of the optical output power with respect to injected current caused by a beam steering phenomenon can be improved, as a result of which an excellent linear characteristic can be obtained in a higher output power range, whereby the ridge waveguide semiconductor laser diode can operate with excellent stability in the transverse and longitudinal modes. In addition, 15 the potential for COD failure is significantly reduced.

[0020] If an FBG is positioned at the front facet of a GaAs-based quantum well laser diode according to the present invention, the GaAs quantum well laser diode operates in a stable output power, and can be used to construct an EDFA having excellent operational characteristics.

20 [0021] The above and other objects, features and advantages of the present invention will be more apparent from the following description, referring to the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

25 [0022] FIG. 1 is a sectional view of a typical ridge waveguide semiconductor laser diode according to the prior art.

[0023] FIG. 2 is a perspective view of a ridge waveguide and its far-field pattern according to the present invention.

[0024] FIG. 3 is a front view of the of the laser diode according to the present 30 invention showing the extent of the light beam generated by the laser.

[0025] FIG. 4-1 is a sectional view of a ridge waveguide semiconductor laser diode according to an embodiment of the present invention.

[0026] FIG. 4-2 is an partial sectional view of a portion of the ridge waveguide semiconductor diode shown in FIG. 4-1 according to the present invention.

5 [0027] FIG. 4-3 is a perspective view of a bar of ridge waveguide semiconductor diodes of FIG. 4-1 according to the present invention.

[0028] FIG. 5 is a graph showing relationship between the kink output power and the ratio D/W according to an embodiment of the present invention.

10 [0029] FIG. 6 is a graph of the difference between the effective refractive index of the mesa structure and the effective refractive index of the remaining cladding layer according to the present invention.

[0030] FIG. 7 is a graph of the light intensity of the far-field pattern along the horizontal axis for a ridge waveguide laser according to the prior art operated at selected drive current levels.

15 [0031] FIG. 8 is a graph of the light intensity of the far-field pattern along the horizontal axis for a ridge waveguide laser according to the present invention operated at selected drive current levels.

[0032] FIG. 9 is a first graph of experimental results of experiments according to the present invention.

20 [0033] FIG. 10 is a second graph of experimental results of experiments according to the present invention.

[0034] FIGS. 11 and 12 are top-plan views of embodiments having tapered-width ridge sections according to the present invention.

25 [0035] FIG. 13 is a sectional view of a ridge waveguide semiconductor laser diode according to another embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[0036] In discussing the present invention, it will be convenient to define some coordinate axes and some terminology. Referring to FIG. 2, we will use a conventional
30 three-dimensional Cartesian coordinate system with three axes: X, Y, and Z. Without

loss of generality, we will orient the length of the laser diode cavity to be parallel to the Z-axis, and the plane of the active layers to be parallel to the X- and Z-axes so that the Y-axis will be normal to the surfaces of the active layers. Again, without loss of generality, we place the front facet of the laser diode at $(X,Y,Z)=(0,0,0)$, and the back (highly reflective) facet at $(X,Y,Z)=(0,0,-L)$, where L is the length of the laser cavity. Within the laser structure, the light propagates parallel to the Z-axis, and along the length of the laser cavity. The Z-axis will sometimes be referred to as the "longitudinal axis," and the modes of the light along this axis will be referred to as "longitudinal modes." Both the X- and Y-axes will sometimes be referred to as the "transverse axes" since they are transverse to the direction of light propagation, with the X-axis being called the "horizontal transverse axis" or the "parallel transverse axis," and the Y-axis being called the "vertical transverse axis" or the "perpendicular transverse axis." The modes of the light along these axes will be referred to as "transverse modes," as is conventional in the art.

[0037] The laser is preferably operated within the fundamental transverse mode, which appears as an oval spot of light at the front facet (*i.e.*, single transverse mode). FIG. 3 is a front view of the front facet of the laser diode showing the oval spot at reference number 1. Oval spot 1 has horizontal width W_H as measured along the X-axis, and a vertical width W_V as measured along the Y-axis. For the purposes of making these width measurements, the peripheral edge of the spot is defined as the locus of points of the spot where the light power level has a value which is $1/e^2$ of the maximum power level at the center of the spot, with "e" being the base of the natural logarithm ($e=2.71828\dots$).

[0038] In practice, the width of the spot is usually measured by projecting the laser spot onto a planar surface spaced at a distance from the laser diode's front facet, and parallel thereto, to form an enlarged version of the spot (*e.g.*, to form a near field pattern). The enlarged spot version is shown at 2 in FIG. 2. The enlarged spot version has the shape of an oval having two axes, a parallel axis 3 which is parallel to the plane of the active layers, and a perpendicular axis 4 which is perpendicular to the plane of the active layers. Because of optical diffraction effects, the width of the spot along

perpendicular axis 4 is larger than the width of the spot along parallel axis 3, which is opposite to case shown in FIG. 3 where the horizontal spot width W_H is larger than the spot vertical width W_V . (When the dimensions of a laser spot are near the wavelength of the emitted laser light, which is most often the case, diffraction effects cause the light emitted from the smaller spot width to spread out with a greater diffraction angle than the light emitted from the larger spot width.) For deriving the value of W_V from the far field pattern, one first finds the two points along perpendicular axis 4 where the optical power is one-half (1/2) of the maximum optical power at the spot center. These two points are located on either side of the spot center, and are indicated in FIG. 2 by the reference numbers 5. The angle formed between the center of the front facet of the laser diode and each of the two points 5 of the enlarged version defines the full angle θ_V of the vertical far-field pattern. This angle is measured by means well known to the art. The vertical spot width W_V may be found from the angle θ_V and the wavelength λ of the emitted light from the following relationship (and its equivalents):

$$W_V = \frac{\lambda}{\pi \cdot \tan\left(\frac{\theta_V}{\sqrt{2} \cdot \ln 2}\right)}, \quad [1]$$

where "ln 2" is the natural logarithm of 2, where "tan" is the tangent function, and where θ_V is provided in the dimensions of radians.

[0039] In a similar manner, for deriving the value of W_H from the far field pattern, the points of one-half maximum power are found on the parallel axis 3 of the enlarged spot version, as indicated at reference numbers 6. The angle formed between the front facet of the laser diode and each of the two points 6 defines the full angle θ_H of the horizontal far-field pattern. This angle is measured by means well known to the art. An analog of the above formula may then be used to derive W_H from θ_H and λ as follows:

$$W_H = \frac{\lambda}{\pi \cdot \tan\left(\frac{\theta_H}{\sqrt{2} \cdot \ln 2}\right)}. \quad [2]$$

[0040] The inventors studied the measures for maintaining the linear relationship between the optical output power and the injected current to prevent the kink

phenomenon. From their studies, the inventors discovered that the optical density in the active layers was inversely proportional to the product of the horizontal width W_H and the vertical width W_V of the optical spot, and that the size of these widths (*i.e.*, the size of the transverse confinement) could be controlled based on the remaining thickness D of the cladding layers overlying the entire surface of the active layers. The remaining thickness "D" as used herein is represented by the thickness of a remaining part of the cladding layers underlying the ridge structure part of the cladding layers. That is, the remaining thickness D is represented in FIG. 4-1 by the overall thickness of the remaining part the layer structure, including the first upper cladding layer 36 and the etch stop layer 34. The remaining thickness D is also indicated in FIG. 3.

[0041] In addition to the above findings, the inventors considered that, in the case of a ridge waveguide semiconductor laser diode having a wide mesa structure for reducing the optical density therein, the beam steering phenomenon does not arise in the high optical output power range, thereby maintaining a constant value for the external differential quantum efficiency η , if a specific relationship holds between the vertical spot width W_V and the remaining thickness D of the cladding layers. As the vertical spot width W_V is important in describing the present invention, we will simplify its notation to "W" in the following discussion.

[0042] The inventors then studied the effects of the above width W and thickness D on what the inventor call the laser's "kink output power level." The kink output power level is the optical output power of the laser at which a significant "kink" first occurs in the normally smooth, linear or quasi-linear relationship between the laser's optical output current L_{OUT} and the laser's drive current I . As indicated above, the slope of the relationship of L_{OUT} versus I is the external differential quantum efficiency " η " ($\eta = dL_{OUT}/d(I - I_{TH})$), which normally has a nearly constant value for drive current I above threshold I_{TH} , or has a curve which quickly reaches an maximum value η_{MAX} for a value of I just above I_{TH} and thereafter decreases gradually as I is increased. A significant kink can be defined as occurring when η undergoes an abrupt decrease of 20%, followed by a rebounding back to near its prior level, when the drive current is changed by a relatively small amount. A significant kink can also be defined as

occurring when η falls to a value of 80% of η_{MAX} as the current is increased beyond the point where η_{MAX} is initially reached. We have used both definitions herein (in other words, if either of the above two conditions occurs, we have counted a kink as having occurred).

5 [0043] Now, the present invention is described more specifically based on a preferred embodiment thereof with reference to the accompanying drawings.

[0044] An epitaxial growth was conducted to form compound semiconductor layers on an n-GaAs substrate 12 by using a Metal Organic Chemical deposition (MOCVD) method to fabricate a layer structure 10 of the GaAs-based semiconductor laser diode
10 shown in FIG. 4-1. The layer structure include the following consecutively formed layers, starting with the bottom layer:

buffer layer 14:	n-GaAs layer,
lower cladding layer 16:	n- $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ layer,
First optical confinement layer 18:	$\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$ layer,
Second optical confinement layer 20:	$\text{GaAs}_{0.94}\text{P}_{0.06}$ layer,
first strained quantum well layer 22:	$\text{In}_{0.2}\text{Ga}_{0.8}\text{As}$ layer,
barrier layer 24:	$\text{GaAs}_{0.94}\text{P}_{0.06}$ layer,
second strained quantum well layer 26:	$\text{In}_{0.2}\text{Ga}_{0.8}\text{As}$ layer,
Third optical confinement layer 28:	$\text{GaAs}_{0.94}\text{P}_{0.06}$ layer,
Fourth optical confinement layer 30:	$\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$ layer,
first upper cladding layer 32:	p- $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ layer,
etch stop layer 34:	p- $\text{In}_{0.5}\text{Ga}_{0.5}\text{P}$ layer,
second upper cladding layer 36:	p- $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ layer,
cap layer 38:	p-GaAs layer.

[0045] Subsequently, a SiN film was formed on the cap layer 38, and used as a mask for etching the second upper cladding layer 36 by a wet etching process using citric acid.
15 The etching process was stopped by the etch stop layer 34, thereby defining the second cladding layer 36 in the shape of a mesa structure, preferably having a width S of 4 μm .

[0046] Then, a second SiN film 44 was formed over the entire surface including the mesa structure. The second SiN film 44 was removed from the surface of the cap layer 38 to expose the cap layer 38. A p-electrode 41 was formed on the exposed portions of
20 cap layer 38 and SiN film 44 (and thereby over the ridge structure part of the upper cladding layer), and an n-electrode 42 was formed on the bottom surface of the substrate 12.

[0047] Thereafter, the bulk device was cleaved to form a laser diode cavity of a desired length, and a dielectric film having a reflectivity of 10% was formed by coating on the front facet (*i.e.*, the low-reflection facet) of the laser structure and another dielectric film having a reflectance of 95% was formed on the back facet (*i.e.*, the high-reflection facet), to complete a semiconductor laser diode. In this manner, the active layers and cladding layers are disposed between the front and back facets. The mesa structure of the second upper cladding layer 36 has a first ridge side disposed between the front and back facets, a second ridge side disposed between the front and back facets, a width S between the first and second ridge sides, and thickness T. The remaining part of the cladding layers (layers 32 and 34) has a first portion underlying the mesa (*i.e.*, the ridge structure part), a second portion which extends away from the mesa by at least a distance R from the first ridge side, and a third portion which extends away from the mesa by at least distance R from the second ridge side, where the distance R is shown in FIG. 4-1. The distance R typically has a value of $2 \cdot W_H$, or more over. Usually, the remaining part of the cladding layer(s) overlies substantially the entire surface of the active layer(s).

[0048] For fabricating the sample semiconductor laser diodes, the thicknesses of first optical confinement layer 18, second optical confinement layer 20, third optical confinement layer 28, fourth optical confinement layer 30, and first upper cladding layer 32 were changed as described later. Each thickness of other layers is fixed as follows:

buffer layer 14:	0.5 μm ,
lower cladding layer 16:	2.0 μm ,
etch stop layer 34:	3 nm,
second upper cladding layer 36:	2.0 μm ,
cap layer 38:	0.5 μm .

[0049] The thickness d1 of the first optical confinement layer 18 was adjusted to be equal to the thickness of the fourth optical confinement layer 30. The thickness d2 of the second optical confinement layer 20 was adjusted to be equal to the thickness of the third optical confinement layer 28. As shown in Table 1, d1 and d2 were set at different

values in each combination of "a" to "i".

	a	b	c	d	e	f	g	h	i
d1 (nm)	100	90	90	70	70	50	50	30	30
d2 (nm)	10	20	10	20	10	20	10	20	10

Table 1

- 5 [0050] By combination of the various values for d1 and d2, the vertical width W (W_v) of the laser spot that results from the set of active layers can be varied. Those active layers include first and second optical confinement layers 18 and 20, first strained quantum-well layer 22, barrier layer 24, second strained quantum-well layer 26, and third and fourth optical confinement layers 28 and 30.
- 10 [0051] In addition, independently of the combination of the values for d1 and d2, the combined thickness "D" of the cladding layers formed between the top of the active layers and ridge cladding layer 36 was set at different values, as indicated in Table 2. For the structure shown in FIG. 4-1, these cladding layers include first upper cladding layer 32 and etch stop layer 36.

Thickness Setting	Thickness value D (μm)
1	0.300
2	0.600
3	0.700
4	0.720
5	0.750
6	0.770
7	0.790
8	0.820
9	0.840
10	0.920
11	0.950
12	0.970
13	1.020
14	1.070
15	1.120

Table 2

15

[0052] In our experiments, different combinations "a" to "i" of d1 and d2 from Table 1 were combined with different settings of combined thickness "D" from Table 2 to form a plurality of secondary combinations. These secondary combinations are indicated in Tables 3-6, where the letter of each secondary combination indicates the primary combination selected from Table 1, and where the number of each secondary combination indicates the thickness setting selected from Table 2. For example, the secondary combination a-6 was formed using the values of d1 and d2 from the primary combination "a" of Table 1, that is d1=100 nm and d2=10 nm, and using the thickness setting "6" from Table 2, D = 770 nm = 0.77 μ m. After forming these secondary combinations, a plurality of laser diodes were constructed, with each laser diode having the thicknesses of its layers determined by the specifications of a corresponding secondary combination. In the experiments, a cavity length of 800 μ m was used.

[0053] Each of the constructed lasers are tested to find the laser optical output power (in mW) at which the first significant kink in the laser output occurred. For the test, the current to the laser was gradually ramped up and the laser's optical power as a factor of the laser current was measured to determine the characteristic of the external differential quantum efficiency η . During the ramping of the current, η will reach a maximum value η_{MAX} before encountering its first significant kink. We will define the kink output power level in these measurements to occur when the first of the following two events occurs:

1. when η first falls to a level which is at or below 80% of η_{MAX} after η_{MAX} is first reached, in which case the kink output power is the laser's output level at that point where η equals 80% of η_{MAX} ;
2. when η undergoes an abrupt decrease of 20% or more, followed by a rebounding back to near its prior level, when the drive current is changed by a relatively small amount, in which case the kink output power is at the inflection point in η where it begins its rebound.

The results of the measurements for the kink output power levels for the secondary combinations are shown in Table 3 to Table 6, together with the value for D in the

combination and the calculated value of D/W (D/W_v).

Combination	$W(\mu m)$	$D(\mu m)$	D/W	Kink output Power level (mW)	Evaluation
a-1	1.12	0.300	0.269	124	NG
a-1	1.12	0.300	0.269	113	NG
a-1	1.13	0.300	0.265	126	NG
a-1	1.15	0.300	0.261	129	NG
a-5	1.14	0.750	0.658	219	G
a-6	1.13	0.770	0.682	205	G
a-6	1.14	0.770	0.673	209	G
b-1	1.16	0.300	0.259	124	NG
b-1	1.17	0.300	0.257	106	NG
b-1	1.17	0.300	0.256	122	NG
b-1	1.17	0.300	0.256	131	NG
b-1	1.18	0.300	0.255	121	NG
b-1	1.20	0.300	0.250	112	NG
b-6	1.16	0.770	0.663	242	G
c-1	1.20	0.300	0.249	125	NG
c-1	1.21	0.300	0.248	131	NG
c-1	1.23	0.300	0.245	118	NG
c-6	1.23	0.770	0.626	190	G
c-6	1.24	0.770	0.622	195	G
c-12	1.22	0.970	0.797	210	G
c-12	1.25	0.970	0.777	296	G
c-15	1.23	1.120	0.911	207	G
c-15	1.24	1.120	0.901	280	G

Table 3

Combination	W(μ m)	D(μ m)	D/W	Kink output Power level (mW)	Evaluation
d-4	1.28	0.720	0.564	191	G
d-7	1.28	0.790	0.619	235	G
d-7	1.28	0.790	0.619	226	G
d-7	1.29	0.790	0.614	205	G
d-7	1.29	0.790	0.612	208	G
d-8	1.25	0.820	0.655	244	G
d-12	1.28	0.970	0.757	296	G
d-12	1.29	0.970	0.751	301	G
d-12	1.30	0.970	0.749	254	G
d-15	1.25	1.120	0.894	267	G
d-15	1.27	1.120	0.884	254	G
e-2	1.33	0.600	0.451	102	NG
e-4	1.32	0.720	0.547	204	G
e-7	1.33	0.790	0.594	196	G
e-8	1.31	0.820	0.628	191	G
e-9	1.31	0.840	0.643	283	G
e-9	1.32	0.840	0.638	245	G
e-10	1.33	0.920	0.691	207	G
e-12	1.31	0.970	0.743	243	G
e-12	1.32	0.970	0.737	203	G
e-13	1.34	1.020	0.761	269	G
e-16	1.32	1.130	0.856	345	G

Table 4

Combination	W(μ m)	D(μ m)	D/W	Kink output Power level (mW)	Evaluation
f-2	1.35	0.600	0.444	138	NG
f-2	1.36	0.600	0.440	131	NG
f-2	1.36	0.600	0.440	118	NG
f-9	1.35	0.840	0.621	252	G
f-9	1.37	0.840	0.612	234	G
f-10	1.39	0.920	0.660	202	G
f-12	1.36	0.970	0.715	197	G
f-12	1.36	0.970	0.715	194	G
f-13	1.39	1.020	0.731	195	G
f-14	1.35	1.070	0.792	261	G
f-14	1.36	1.070	0.785	296	G
f-14	1.41	1.070	0.761	209	G
f-15	1.36	1.120	0.822	271	G
g-2	1.42	0.600	0.422	142	NG
g-3	1.45	0.700	0.484	143	NG
g-10	1.45	0.920	0.636	238	G
g-11	1.45	0.950	0.657	254	G
g-12	1.42	0.970	0.684	298	G
g-13	1.42	1.020	0.720	302	G
g-13	1.44	1.020	0.708	218	G
g-13	1.42	1.030	0.724	256	G
g-14	1.41	1.070	0.758	226	G

Table 5

Combination	W(μ m)	D(μ m)	D/W	Kink output Power level (mW)	Evaluation
h-3	1.49	0.700	0.470	167	NG
h-13	1.46	1.020	0.697	215	G
i-3	1.52	0.700	0.461	158	NG
i-3	1.53	0.700	0.457	127	NG
i-6	1.50	0.770	0.513	235	G

Table 6

[0054] A kink output power level of at least 200 mW is desired in a practical GaAs-based quantum-well laser diode. In Tables 3-6, each secondary combination which produces a laser diode having a kink output power of 200 mW or more is evaluated as passing (G), each combination which produces a laser diode having a kink output power of less than 200mW is evaluated as failing (NG).

[0055] From the above results, when $D/W \geq 0.5$, the evaluation is "G". A practical GaAs-based quantum well laser diode having a high output power is achievable by having a relationship $D/W \geq 0.5$.

[0056] The critical meaning of the configuration that the thickness D is equal to or larger than a half the vertical spot width W (*i.e.*, $D/W \geq 0.5$) is further detailed.

[0057] FIG. 5 shows the relationship between the kink output power and the ratio D/W, wherein the kink output powers (mW) tabulated in Tables 3 and 6 are plotted on the abscissa, and the ratios D/W tabulated on Tables 3 and 6 are plotted on ordinate. As seen from FIG. 5, in the range where $D/W \geq 0.5$, the kink output power is above 190 mW or substantially above 200 mW, which is sufficient for the semiconductor laser diode, whereas in the range where $D/W < 0.5$, the kink output power is below about 170 mW, or more accurately, below 167 mW. That is, a clear difference as high as 20 mW appears in the kink output power between the former range and the latter range. The difference is technically significant for the characteristics of the ridge waveguide semiconductor laser diode, and thus the ratio $D/W=0.5$ has a critical meaning therein.

[0058] Further studies revealed that there is a preferred upper limit for the ratio D/W when the output of the laser diode is optically coupled to a fiber-Bragg grating (FBG) or

other wavelength selector. In the experiments conducted, a larger remaining thickness "D" resulted in a reduction in the difference Δn between the effective refractive index n_M of the mesa structure and the effective refractive index n_R of the remaining cladding layer ($\Delta n = n_M - n_R$). The effect of the remaining thickness D upon Δn is shown in FIG.

5 6. A larger remaining thickness D above a threshold value intensified the gain guide mode in the mesa structure, which reduced the mode control effect (stability) of the mechanism in the waveguide that stabilizes the fundamental transverse mode, and in turn induced a kink phenomenon along with a reduction in the stability of the fundamental transverse mode. As a result, a beam-steering effect occurs in the far field
10 pattern (FFP) whereby the center of the laser spot in the FFP shifts horizontally along the X-axis and away from the center axis defined by the laser cavity (e.g., the Z-axis) during operation or when the drive current is varied through the laser's current range. The horizontal shift is called a fluctuation. In addition, there may be some spurious side humps or minor side peaks which occur in the FFP, the latter of which normally has a
15 Gaussian-like shape. A side hump in the FFP is also call a fluctuation. FIG. 7 shows the FFP patterns of a prior art device along the horizontal axis (Y-axis) at selected drive current levels (200 mA, 300 mA, 400 mA, and 440 mA) which produce corresponding optical output power levels in the laser. The FFP patterns for 200 mA and 300 mA are normal and have a Gaussian-like shape. However, the FFP pattern for 400 mA has a
20 side hump, and the FFP pattern for 440 mA has multiple side humps and its peak is shifted about -3 degrees from the peak positions of the other FFP patterns. We define a stable (fundamental) transverse mode as a state in which, during the operation of the laser and as the laser's current is varied through the laser's operating range, the peak stays within 1 degree of its center value. We define an unstable (fundamental) mode as
25 a state in which the beam peak shifts by more than 1 degree in the FFP during the operation of the laser or as the laser's current is varied through the laser's operating range.

[0059] The studies further revealed that the unstable fundamental transverse mode due to the larger remaining thickness D caused an unstable longitudinal mode in the lasing
30 wavelength of the ridge waveguide semiconductor laser diode, and thus caused the

optical output power to fluctuate when a FBG was positioned in front of the front facet of the semiconductor laser diode. We define a "stable longitudinal mode" as a state where the lasing wavelength of the laser is relatively fixed at a single wavelength, and an "unstable longitudinal mode" as a state where the lasing wavelength changes

5 between a single wavelength and multiple wavelength values during the operation of the laser. The studies revealed that the relationship $D/W \geq 0.5$ is not sufficient for achieving the need for a high degree of stability in the longitudinal and transverse modes of the laser output when operating the laser in a higher output power range when using an FBG. Without finding the upper limit of the ratio D/W , it is difficult to
10 provide a ridge waveguide semiconductor laser diode having a higher desired output power for the development of WDM systems, or provide a ridge waveguide laser diode for use as a light source for an optical module having an FBG or being used with an FBG.

[0060] In view of the above, the present inventors conducted further studies to find the
15 preferred upper limit of the ratio D/W with the following experiments.

[0061] In the experiments, samples for the semiconductor laser diodes each having the remaining thickness D and width W tabulated in Tables 7 and 8 were fabricated, operated for a higher optical output power, and evaluated in connection with the fluctuations in the far-field pattern (FFP).

20 [0062] In the evaluation, samples exhibiting a larger fluctuation in the FFP (greater than 1 degree), which generally causes a lower stability, were judged as failing devices, whereas samples exhibiting a lower fluctuation in the FFP (1 degree or less), which generally results in relatively higher stability in the transverse mode, were judged as passing devices. The results of the evaluation is shown in Tables 7 and 8.

Sample No.	W (μm)	D (μm)	D/W	Evaluation
1	1.26	0.98	0.78	G
2	1.26	1.13	0.90	G
3	1.16	1.02	0.88	G
4	1.30	1.46	1.12	NG
5	1.34	0.97	0.72	G
6	1.43	0.96	0.67	G
7	1.46	1.23	0.84	G
8	1.30	1.01	0.78	G
9	1.27	0.99	0.78	G
10	1.47	0.79	0.54	G
11	1.65	1.52	0.92	G
12	1.56	1.62	1.04	G
13	1.29	1.78	1.38	NG
14	1.27	1.68	1.32	NG
15	1.60	1.4	0.88	G
16	1.64	1.52	1.06	G
17	1.40	1.64	1.17	NG
18	1.28	1.64	1.28	NG
19	1.45	1.58	1.09	NG
20	1.34	1.48	1.10	NG
21	1.47	1.95	1.33	NG
22	1.57	1.59	1.01	G
23	1.48	1.41	0.95	G
24	1.51	1.55	1.03	G
25	1.63	1.73	1.06	NG

Table 7

Sample No.	W (μm)	D (μm)	D/W	Evaluation
26	1.79	1.65	0.92	G
27	1.42	1.61	1.13	NG
28	1.48	1.56	1.05	G
29	1.77	1.94	1.10	NG
30	1.60	1.28	0.80	G
31	1.44	1.17	0.81	G
32	1.78	1.35	0.76	G
33	1.64	1.67	1.02	G
34	1.50	1.84	1.23	NG
35	1.62	1.54	0.95	G
36	1.48	1.47	0.99	G
37	1.85	1.95	1.05	G
38	1.63	1.76	1.08	NG
39	1.51	1.2	0.79	G
40	1.99	1.36	0.68	G
41	1.74	1.33	0.76	G
42	1.62	1.5	0.93	G
43	1.68	1.58	0.94	G
44	1.72	1.44	0.84	G
45	1.85	1.83	0.99	NG
46	1.63	1.35	0.83	G
47	1.67	1.43	0.86	G
48	1.64	1.24	0.76	G
49	1.54	1.11	0.72	G
50	1.72	1.57	0.91	G

Table 8

- [0063]** As seen from Tables 7 and 8, except for some minor variations, the ratio D/W=1 to D/W=1.1 exhibits a critical significance, wherein the judgement is “NG”, or failing, for the range D/W >1.1, and the judgement is “G”, or passing, for the range D/W<1, with many judgements being passing in the range of D/W=1.0 to D/W=1.1. The results of Tables 7 and 8 are plotted in FIG. 9. FIG. 8 shows the far-field patterns of a device constructed according to the present invention at the same current levels used in the prior art example of FIG. 7.

[0064] Based on the findings as detailed above, a ridge waveguide semiconductor laser diode according to the present invention has a structure which satisfies:

$$1.10 > D/W \geq 0.5$$

and more preferably satisfies:

$$1.05 > D/W \geq 0.5$$

and most preferably satisfies:

$$1.0 > D/W \geq 0.5$$

5 for the remaining thickness D of the cladding layer formed on the active layer or layers, and for the vertical spot width W providing an intensity $1/e^2$ for the near-field pattern in the vertical direction or the direction normal to the active layer. Combined data from the experiments according to the present invention are plotted in FIG. 10, where the result of a constructed laser is plotted with a diamond symbol for a laser with a stable
10 high kink output power and an "x" symbol for a laser with an unstable transverse mode, an unstable longitudinal mode, and/or a low kink output power level. Each shown laser is plotted along the abscissa according to laser's W value, and along the ordinate according to the laser's D value.

[0065] The cladding layer may be an upper cladding layer or a layer having a similar
15 function and formed over the entire surface of the active layer or layers.

[0066] The present invention is applicable to any ridge waveguide semiconductor laser diode such as InP- or GaN-based laser diodes in addition to the GaAs-based semiconductor laser diodes. It is also applicable to such a laser diode irrespective whether or not the active layer has a quantum well structure.

20 [0067] The present invention is suitably applicable to such a laser diode irrespective of the width of the mesa structure of the ridge waveguide. However, the present invention is preferably applied to a ridge waveguide semiconductor laser diode having a mesa structure which is 4 μm wide or more ($S \geq 4 \mu\text{m}$).

[0068] Now, the present invention is more specifically described with reference to
25 accompanying drawings, wherein similar constituent elements are designated by similar reference numerals throughout the drawings.

[0069] Referring to FIG. 4-1, a ridge waveguide semiconductor laser diode, generally designated by numeral 40, according to a first embodiment of the present invention has a layer structure similar to the layer structure of the semiconductor laser 10 shown in
30 FIG. 1 except that the overall remaining thickness D in the present embodiment, which

is defined by the sum of thicknesses of the layers including the first upper cladding layer 32 and the etch stop layer 34, satisfies the following relationship:

$$1.10 > D/W \geq 0.5.$$

The contents of the layers in the present embodiment are similar to those of the samples used in the first and second experiments.

[0070] More specifically, the laser diode 40 of FIG. 4-1 has a n-type GaAs substrate 12, and a layer structure grown thereon and including:

	n-GaAs	buffer layer 14;
	n-Al _{0.3} Ga _{0.7} As	lower cladding layer 16;
10	Al _{0.2} Ga _{0.8} As	first optical confinement layer 18;
	GaAs _{0.94} P _{0.06}	second optical confinement layer 20;
	In _{0.2} Ga _{0.8} As	first strained quantum well layer 22;
	GaAs _{0.94} P _{0.06}	barrier layer 24;
	In _{0.2} Ga _{0.8} As	second strained quantum well layer 26;
15	GaAs _{0.94} P _{0.06}	third optical confinement layer 28;
	Al _{0.2} Ga _{0.8} As	fourth optical confinement layer 30;
	p-Al _{0.3} Ga _{0.7} As	first upper cladding layer 32;
	p-In _{0.5} Ga _{0.5} P	etch stop layer 34;
	p-Al _{0.3} Ga _{0.7} As	second upper cladding layer 36; and
20	p-GaAs	cap layer 38.

The thicknesses of the first optical confinement layer 18, second optical confinement layer 20, third optical confinement layer 28, fourth optical confinement layer 30 and first upper cladding layer 32 are determined as detailed later. The thicknesses of the remaining layers are as follows:

Buffer layer 14:	0.5 μm ,
lower cladding layer 16:	2.0 μm ,
etch stop layer 34:	3 nm,
Second upper cladding layer 36:	2.0 μm ,
Cap layer 38:	0.5 μm .

25

[0071] By employing the configuration wherein the first optical confinement layer 18

and the fourth optical confinement layer 30 have the same thickness d_1 , and the second optical confinement layer 20 and the third optical confinement layer 28 have the same thickness d_2 , with d_1 and d_2 being changed for obtaining a variety of combinations of thicknesses, the vertical spot width W (W_v) at the laser front facet that results from the set of active layers can be varied. Those active layers include first and second optical confinement layers 18 and 20, first strained quantum well layer 22, barrier layer 24, second strained quantum well layer 26, and third and fourth optical confinement layers 28 and 30.

[0072] The width S of the mesa structure for the above layer diode is set at $4\ \mu\text{m}$.

- 10 [0073] A laser diode device according to the present invention may be constructed in the following manner. As a first step, a desired value for the vertical spot width W (W_v) is selected based on the needs of the application that the laser will be used in, or on other criterion important to the user. Oftentimes, the user will want the vertical divergence angle θ_v of the laser beam to be within a selected range of values, and the user may use the above equation [1] to select a value of W based on a desired value of θ_v . Based on the selected value of W , the user can then consult Tables 3-6 to find thickness values d_1 and d_2 of the optical confinement layers which provide values of W near or at the selected value of W , or the user may construct his own matrix of devices which have different thicknesses of the active layers and different values of D to find a range of constructions to select from to achieve a desired value of W . Finally, the value of the remaining thickness D may then be selected within the range of $1.10 > D/W \geq 0.5$, which is equivalent to $1.10 \times W > D \geq 0.5 \times W$, or within the more preferred range of $W > D \geq 0.5 \times W$. As an example, when the desired spot size width " W " is $1.3\ \mu\text{m}$, the value for " D " is selected such that $1.43\ \mu\text{m} > D \geq 0.65\ \mu\text{m}$ for the larger range, that is, D is equal to or greater than $0.65\ \mu\text{m}$ and less than $1.43\ \mu\text{m}$, and is selected such that $1.33\ \mu\text{m} > D \geq 0.65\ \mu\text{m}$ for the most preferred range. More specifically, the thicknesses of first upper cladding layer 32 and the etch stop layer 34 are selected so that the remaining thickness D is lower than $1.43\ \mu\text{m}$, but is not lower than $0.65\ \mu\text{m}$ for the larger range; and are selected so that the remaining thickness D is lower than $1.33\ \mu\text{m}$, but is not lower than $0.65\ \mu\text{m}$ for the most preferred range.

[0074] The remaining thickness "D" in FIG. 4-1 is defined by the sum of thicknesses of the layers disposed between fourth optical confinement layer 30 and the mesa structure, that is, layers including first upper cladding layer 32, etch stop layer 34, and any additional layers that the user may add between fourth optical confinement layer 30 and the mesa structure, with the additional layers functioning as cladding material with respect to the optical confinement layers and/or the active layers.

[0075] In the present embodiment, although the etch stop layer 34 made of $\text{In}_{0.5}\text{Ga}_{0.5}\text{P}$ is used for controlling the remaining thickness "D" of the cladding layer remaining above the active layers, it is possible to control the remaining thickness "D" by using another etch stop layer or another method instead of using an etch stop layer, and thus the presence of etch stop layer 34 is not necessary for practicing the present invention.

[0076] As described above, the ridge waveguide semiconductor laser diode of the present embodiment has an excellent linear relationship between the optical output power and the injected current due to the relationship $D/W \geq 0.5$, and operates with excellent stability in both the transverse and longitudinal modes at a higher optical output power due to the relationship $1.10 > D/W$.

Further Preferred Embodiments.

[0077] Referring back to FIG. 4-1, in further preferred embodiments, p-electrode 41 comprises a metal layer having a thickness of more than $0.6 \mu\text{m}$, and preferably a thickness of approximately $1.5 \mu\text{m}$ (the thickness being measured at the centerline of the mesa of the ridge structure part, or at the flat areas to the sides of the mesa). The range of thickness between $0.6 \mu\text{m}$ and $1.5 \mu\text{m}$ reduces thermal gradients and fluctuations in the device. The metal layer may comprise evaporated gold material, or a tri-layer structure of a titanium (Ti) sub-layer, a platinum (Pt) sub-layer, and gold sub-layer (Au, which may also comprise evaporated material), as shown in partial exploded view of FIG. 4-2.

[0078] In further preferred embodiments of the present invention, the cavity length between the front and back facets is not less than 1 millimeter (mm). In addition, before the low-reflective and high-reflective dielectric films are formed on the front and back

facets, respectively, the front and back facets are coated with a passivation layer 46, as shown in the partial perspective view of FIG. 4-3. In preferred embodiments, the passivation layer 46 comprises a semiconductor material, such as silicon (Si), germanium (Ge), antimony (Sb), and compounds of antimony, such as AlSb, GaSb, and InSb. Passivation layers of these materials may be formed on the facets by semiconductor-layer growth processes, such as MBE, CVD, and MOCVD, or by sputtering or electron beam deposition, if appropriate for the material. Passivation layer 46 is preferably substantially oxygen-free, and the interface between passivation layer 46 and each facet is preferably substantially oxygen-free. The reduction in oxygen content reduces light absorption in layer 46 and at the interface between layer 46 and the facet. As used herein, a concentration level of $1 \times 10^{17} \text{ cm}^{-3}$ or less of oxygen atoms in the layer (or material around the interface with the facet) is considered to be substantially oxygen free. Preferably, the concentration level is maintained below $1 \times 10^{16} \text{ cm}^{-3}$. These concentration levels may be readily achieved by cleaving the bulk device within a controlled atmosphere that has less than 1 ppm of oxygen and less than 1 ppm of water, transferring the cleaved devices to a growth chamber within a similarly controlled atmosphere, and thereafter growing the passivation layer within a controlled atmosphere that has less than 1 ppm of oxygen and less than 1 ppm of water. The above cavity length and passivation features increase the maximum output power of the laser diode, and may be used in combination with previously described features.

[0079] In yet further embodiments of the present invention, the ridge width S (see FIG. 4-1 for definition of S) is tapered along the length toward the back facet for at least a portion of the cavity length, as shown in the top plan view of FIG. 11. FIG. 11 shows laser diode 40 after the second upper cladding layer 36 has been etched to define the mesa ridge, and before SiN film 44 and p-electrode 41 have been formed. The tapered section is preferably located closer to the front facet than the back facet, with the widest part of the tapered section being closest to the front facet. A section of uniform width extends from the tapered section to the back facet. For both of these sections, the width S is preferably not less than $4 \mu\text{m}$. An additional short section of uniform width may be added between the front facet and the tapered section, and a short tapered section may

be added between the long section of uniform width and the back facet.

[0080] In FIG. 11, the shape of the tapered section is substantially linear. However, the taper may be concave (e.g., parabolic) as shown by the solid line in FIG. 12, or may be convex (e.g., exponential) as shown in the dashed line in FIG. 12.

5 [0081] The above tapered-width features reduce catastrophic optical damage (COD) at the front facet, and may be used in combination with previously described features.

[0082] The present invention may be practiced on a lasers made from a variety of compound-semiconductor material systems, emitting light over a broad wavelength spectrum, such as 700 nm to 1550 nm. Embodiments using the GaAs material system with an InGaAs well layer illustrated above with respect to FIG. 4-1 emit light at a wavelength of 980 nm or in a wavelength band around 980 nm, an example of such a band has a wavelength range from 850 nm to 1120 nm. In FIG. 13, we illustrate the formation of an embodiment 220 based on the InP material system, and which emits light at 1480 nm, or in a wavelength band near 1480 nm, an example of such a band has a wavelength range from 1300 nm to 1550 nm.

15 [0083] On the (100) surface of an n-InP substrate 201, the following layers are sequentially formed: an n-InP lower cladding layer 202 working as a buffer layer, a graded-index separate confinement heterostructure multi-quantum well (GRIN-SCH-MQW) active layer 203, a p-InP upper cladding layer 205, and a p-InGaAsP contact layer 207. A part of the p-InP upper cladding layer 205 and the p-InGaAsP contact layer 207 are etched to form a mesa stripe (*i.e.*, a ridge structure part). Active layer 203 is formed from GaInAsP material, where the percentages of the elements may be varied according to conventional practice to provide the bandgap envelope of the GRIN-SCH-MQW structure. Thereafter, an SiN (e.g., SiN_x) layer 209 is formed over the mesa stripe and remaining part of cladding layer 205, and then patterned at the top of the mesa to form a contact area. This mesa stripe (*i.e.*, a ridge structure part) thereby realizes a current injection function, and a light confinement function which utilizes a difference between the refractive index of air and the refractive index of the semiconductor (*i.e.*, the p-InP upper cladding layer 205). A p-side electrode 210 is formed to cover an exposed portion of the p-InGaAsP contact layer 207 and the surface

of the SiNx film 209. Based on this, the p-side electrode 210 and the p-InGaAsP contact layer 207 are electrically contacted to each other. Electrode 210 may have any of the above described features of electrode 41. An n-side electrode 211 is formed on the rear surface of the n-InP substrate 201. The devices are then cleaved to a desired
5 cavity length, such as 1 mm or more, and a passivation layer 46 may be formed on the facets, as described above. The width of the mesa ridge part may be tapered, as described above.

[0084] Since the above embodiments are described only for examples, the present invention is not limited to the above embodiments and various modifications or
10 alterations can be easily made therefrom by those skilled in the art without departing from the scope of the present invention. While the present invention has been particularly described with respect to the illustrated embodiments, it will be appreciated that various alterations, modifications and adaptations may be made based on the present disclosure, and are intended to be within the scope of the present invention.

15 While the invention has been described in connection with what is presently considered to be the most practical and preferred embodiments, it is to be understood that the present invention is not limited to the disclosed embodiments but, on the contrary, is intended to cover various modifications and equivalent arrangements included within the scope of the appended claims.